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Methods of Testing Solid Dielectrics

Electrical Engineering

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METHODS OF TESTING SOLID DIELECTRICS

BY

LADISLAV VACLAV ČAPEK
LEROY STEWART FOLTZ

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING
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May 27 1911

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Ladislav Vaclav Capek and Leroy Stewart Foltz

ENTITLED Methods of Testing Solid Dielectrics

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

J M Bryant
Instructor in Charge

APPROVED: Ernst Berg

HEAD OF DEPARTMENT OF Electrical Engineering

197575

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METHODS OF TESTING SOLID DIELECTRICS

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METHODS OF TESTING SOLID DIELECTRICS

I - INTRODUCTION.

In all electrical machinery the question of proper and efficient insulating material is one of extreme importance..The kind of material that is used will depend largely upon the special requirements of the particular service for which it is intended. In most cases, among other minor specifications, there is a demand for, (1) Dielectric Strength, (2) Insulation Resistance, and, (3) Durability. The first of these, dielectric strength, has within the last few years become recognized as the most important quality desired in insulation.

Thus, as far back as 1897, Dr. C.P. Steinmetz says, "I am glad to state that more and more consulting electrical engineers come back from this question of the megohms insulation resistance as a guarantee of the safety of the insulation of the machine, and instead of it, specify the voltage at which the insulation should not be punctured." (Trans. American Institute Elect. Engrs. Vol.XIV, 1897.) Holitscher contributes the following,"It cannot be emphatically enough stated that the disruptive strength rather than the megohm resistance is generally the true measure of the usefulness of an insulating material." (Electrotechnische Zeitschrift, 1902.) Making use of still another quotation we have, "What is wanted in electrical machinery is high disruptive strength, that is, great power of withstanding high voltage without sustaining injury or initiating deterioration, and modern specifications should aim that a piece of completed apparatus shall be able to withstand under test the application of a voltage in excess of the highest voltage to which it ever

will be subjected in normal operation." (Turner & Hobart, Insulation of Electric Machinery, p. 6) When these quotations from different sources are considered in connection with the recommendation of the American Institute of Electrical Engineers it is evident that the matter of the disruptive strength of insulating material is one of supreme importance.

"A thing insulates because it is possessed of two distinct properties; First, the ability to stand the mechanical and electrical stresses due to the voltages used, and second, because it is such a poor conductor that but a negligibly small current can flow thru it and leak away. The first property is called the dielectric strength, ------the other property is called the ohmic resistance."(R.A.Fessenden, Insulation and Conduction, Trans. A.I.E.E. Vol. XV, 1908) In the Standardization Rules of the American Institute of Electrical Engineers, the following definition is given. "The dielectric strength of an insulating wall, coating, cover, or path is measured by the voltage which must be applied to it in order to effect a disruptive discharge thru the same." (Sect. E-II-214) Dielectric strength in this thesis will be taken to mean the voltage at which the material ruptures and allows a discharge to pass.

The realization of the importance of the dielectric strength of insulating material has caused many tests to be made to determine this quality. Investigation of the literature on this subject brings to light many seemingly contradictory results. Each experimenter has used a different form of apparatus and a comparison of the widely differing results becomes a hopeless task. Lately, one of the National Testing Societies, endeavoring to arrive at some basis for comparing various insulating materials in the market, appointed a committee whose task it is to design some form of apparatus and method of test-

ing dielectrics. This then, is the situation at the present time.

From a review of the various forms of apparatus and methods thus far used in testing dielectrics, it appears that the following conditions are essential, viz.,

1- Apparatus should give uniformity in results.

2- Its form should be applicable to any kind of solid dielectric and permit ready interpretation of results.

3- It should, if possible, duplicate the conditions existing in the actual use of the dielectric.

For the realization of the foregoing it seems to be desirable to have

1- A sine wave of impressed electromotive force at a constant frequency.

2- A uniform and gradual rise of voltage from zero to the rupturing value, to avoid the transient effects of the higher harmonics.

3- An absence of sharp edges and points which distort the electrostaric field and cause an accurate interpretation to be impossible.

4- Uniformity in temperature and moisture conditions since these are influential in determining the dielectric strength of many materials.

As nearly perfect contact as possible between the electrodes and the material under test.

It is with a hope of contributing something toward an apparatus and method of testing dielectrics under these more or less ideal conditions that this thesis is written.

II GENERAL THEORY

The conductor of electricity is the center and seat respectively, of an electromagnetic and electrostatic field. The former is directly proportional to the current flowing in the conductor while the latter is directly proportional to the voltage causing the current to flow and to a constant depending upon the medium surrounding the conductor. This constant is the inductivity of the medium and is equal to unity for air. With high voltage and small current, a condition existing in tests of dielectrics, the electrostatic field assumes extreme importance while the other is relatively unimportant.

The field due to an electrostatic charge may be considered as consisting of tubes or lines of force originating and ending upon the electrified surface. These tubes, which are assumed to be in a state of tension, also repel each other. This results in putting the medium in which they exist into a strained condition. The resultant force on all points of an electrified surface due to these electrostatic lines is in a direction normal to that surface. The intensity of the field at any given point in the neighborhood of a sphere will be proportional to the force acting on a unit charge of electricity placed at this point. With a charge "e" electrostatic units on the surface of an isolated sphere, the intensity at any point r cm. from it is equal to $\frac{e}{Kr^2}$ where K is the inductivity of the medium.

With two electrified surfaces placed close together, the distribution of the charge on each of these is changed from that existing when each surface was uninfluenced by the other. The charge on any surface for given external conditions is determined by the potential of that surface. The potential of a surface is defined as the work which must be done to bring a positive unit quantity of electric-

ity from an infinite distance to the surface against the action of the electrostatic field. The field between the two conductors near together becomes a combination of the single uninfluenced field of each conductor. The difference of potential between two surfaces is then, the work which must be done to carry a positive unit quantity of electricity from the surface of lower to the one of higher potential. Work is force times distance. Figure A shows the distribution of the field about two spheres near together. Between the spheres the field is intense, i.e. the dielectric flux per unit area is large. Further out the intensity decreases. Since the drop of voltage per unit length along a path is greatest between the spheres, large potential gradient is synonymous with great intensity of electrostatic field. The intensity of the field is greatest at the sphere surface since the flux remains the same and this is the region of minimum area. As the diameter of the sphere is increased, the surface of a plane is approached as a limit. With a plane of infinite dimensions, the field would be normal to the surface and uniform in intensity at all points. With a plane of finite dimensions, the edges, which may be considered as having small curvature, will have a field of great intensity. The distribution of the charge will be as indicated by Fig. B. Due to the absence of the restraining influence of plates, the field at the outer portion of the plates will spread in the manner indicated, the resulting field becoming complex and indeterminate.

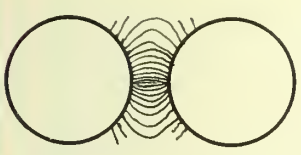


Figure A.

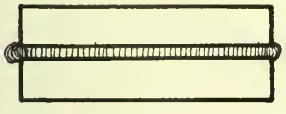


Figure B.

This brief exposition of the underlying principles of the electrostatic field paves the way for a study of the problems found in dielectric testing. The breakdown of a dielectric is caused by an application of a high voltage. This

results in an electrostatic field accompanied by the appearance of corona. The rupture of the dielectric may be considered as due to two factors; (1) Intra atomic forces resulting from the field due to high voltage, (2) The deterioration of the dielectric due to the heating accompanying corona. Each of these factors will be considered.

The electrostatic field surrounding the dielectric placed between the testing electrodes or charged surfaces causes a distortion of the atomic structure in the tested material. Assuming the electronic theory of matter, the displacement of the free electrons due to the distorting field, while in progress, constitutes an electric current. This displacement is resisted by the dielectric, and with an alternating electromotive force, is the cause of an energy loss due to what Dr. C.P. Steinmetz has termed "dielectric hysteresis." We have here a condition almost analogous to magnetic hysteresis. In fact, tests made to ascertain the extent of this loss have discovered effects parallel to those existing in an iron magnetic circuit. The current first rises steadily with increasing voltage, then reaches a saturation point and just before rupture, rises to a higher value. This has the elements of a stress curve for iron or similar material. When the intra atomic stresses become too great for the structural strength of the material to withstand them, rupture ensues. The voltage at rupture is the dielectric strength of the material.

The second cause for rupture, though it appears a minor one in most cases, is that due to the weakening effect of the heating produced by the charging and corona current. Dr. C.P. Steinmetz found in his studies of the disruptive strength of materials, that the atmosphere surrounding strong dielectrics and the electrodes applied thereto would break under the strain formed by the flux of electrostatic force thru it much more readily than the material under test. The

following reasoning will explain this. Assuming two plates as in Fig. C separated in air at a distance "r" from each other and with a difference of potential equal to "E" volts, the following is true if this air column is just sufficient to withstand this voltage. Let "e" be the intensity of field or potential gradient at any point between the electrodes since the field is assumed uniform. From the definition of potential, we have $E = er$. If now, conditions are as shown in Fig. D we have the following result. Assume that the inductivity of the dielectric "d" equals K_1 and is greater than unity. With the same potential difference assumed between the plates,

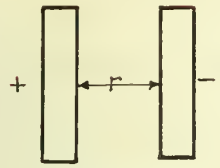


Figure C.

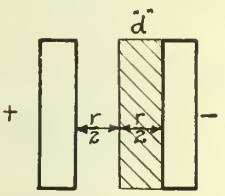


Figure D.

$$\frac{e'r}{2K_1} + \frac{e'r}{2} = E$$ where e' is the new intensity within the complex dielectric. $\frac{e'r}{2}\left(\frac{1}{K_1} + 1\right) = er$, or $\frac{e'}{2}\left(\frac{1}{K_1} + 1\right) = e$ Hence, $e' = \frac{2eK_1}{K_1 + 1}$ is the new intensity of the field in the air film. With $K = 4$, $e' = \frac{8e}{5}$ or $1.6(e)$. Thus the stress per unit length of air film is increased, breaking down the air and throwing the whole stress on the dielectric "d".

If the plates are brought together the result is similar. The air surrounding the dielectric is weaker than the dielectric itself and the tendency of the charge to leak thru this air results in its breaking down. This gives rise to an envelope of conducting atmosphere surrounding the dielectric. This phenomenon, which has the appearance of the brush discharge, was given the name Corona by Dr. C.P.Steinmetz

Later investigators, notably Nipher, (American Academy of Science, St. Louis, June 1910) and Ryan (Trans. American Institute of Electrical Engineers, Feb. 1910) give the following explanation of corona, based on the electronic theory. Under ordinary conditions the

plates are in a region of partly ionized air and of non-conducting dust particles which become radioactive under the action of the electrostatic field. The electrification of the plate results in the liberation of negative electrons on its surface, which by reason of electrostatic action, are repelled from the negative plate and tend to migrate toward the positive plate. If the field is strong enough, the electrons attain sufficient velocity to cause the ionization of the air particles with which they collide. This result may be also secured by further liberation of negative electrons from the positive plate by impact. The initial ionization results in a flow of current which reduces the resistance of the path and causes a still greater ionization to take place. This process continues until equilibrium for this voltage is reached. With an alternating electromotive force the negative electrons travel with a double frequency synchronous advance and retreat. The retreat toward the electrode, due to a combination of factors, is at a greater rate than the advance and hence the electrons during these migrations will strike the electrode giving further ionization at critical velocity. Dr. C.P. Steinmetz states that corona is not only dependent upon the critical voltage at the surface of the plate, but also upon the volume of air over which the critical voltage has been exceeded. (Gen. Elect. Review, Mar. 1911.) As soon as this finite volume is reached, current flows which is made apparent by the appearance of a bluish light. This flow of current results in heating which, if long continued, causes a deterioration of the material and a consequent breakdown.

The streams of electronic charges are surrounded by electrostatic and electromagnetic fields. The former causes the streams to spread, the latter, to form them into a core. When the number of electrons becomes large enough so that the electromagnetic attraction

overcomes the electrostatic repulsion, a solid stream of electrons is formed which has a conducting core. A disruptive discharge will then pass along this path. This happens in tests of dielectrics, discharge taking place over the surface of and around the dielectric. It is thus evident that the presence of corona is an indication of an intense stress with a possibility of a breakdown occurring at that point.

On page 5 it was stated that the potential gradient, and hence the electric intensity, was uniform thruout the air between the electrodes. It seems reasonable to suppose that this would also be true for any solid homogeneous dielectric, that is, the breakdown voltage of a dielectric should vary directly with the thickness. Such a relation, if it exists, has not up to the present time been discovered. It appears reasonable to suppose that after a certain critical thickness is reached, the apparent resistance of the material due to dielectric hysteresis would confine the greatest stress to the contact surfaces, resulting in a progressive breakdown and an apparently lower strength. All these deductions, while theoretically feasible, have not as yet been experimentally proven and so provide an interesting and fruitful field for research.

III - PRELIMINARY INVESTIGATIONS

(a) APPARATUS

The apparatus used in these tests is shown on Plate I. The standards to which the high tension leads were attached, were of one inch brass tubing. Fig. 8 on Plate II has a view of a section of these standards. The sketch shows the method of attaching the various electrodes. A conical seating insured a uniform contact of the lower terminal with the insulating material to be tested. A weight placed in the pan on the upper standard was used to improve this contact.

As has been indicated under "General Theory", the form of electrode is of prime importance and for this reason various types of these were tried. They were made of brass because of the ease with which machining and finishing are done on this metal. Investigators are agreed that the metal used for this purpose has no effect upon the results. These terminals are shown on Plate II, numbered from one to ten inclusive, and reference to them will hereafter be made by these numbers..

The power for the preliminary tests was obtained from a Gen. Electric Co's. 2 phase, 45 K.W. 440 Volt, 60 Cycle, Alternating Current Generator driven by a D.C. Shunt Motor of the same make and size. Only one phase was used and the generator carried no other load. The voltage was stepped down to 110 volts and delivered to the terminals of a potentiometer control resistance. Plate I has a diagram of the wiring. From the control resistance, connection was made to two Gen. Electric Co's. 50 Watt, 110-11000 Volt, Instrument Transformers, having their primaries connected in parallel and the high tension secondaries in series. A resistance of 46.5 ohms was connected in parallel across the primaries as indicated on the diagram of wiring.

The transformers and the control resistance had the following characteristics;

Total impedance of coil	.....	81.2	ohms.
" reactance "	.....	14.6	"
" resistance "	.....	67	"
Average impedance of coil in circuit	...	68.6	"
" reactance " "	...	12.3	"
" resistance " "	...	56.5	"

The transformers each took approximately .5 ampere charging current on 110 volts. Curves of charging current taken at different voltages are shown on Plate III.

The circuit was completely controlled by two switches connected in series, one of them operated by a depressible platform placed in front of the testing apparatus to protect the operator from unwittingly coming in contact with the high tension leads.

III- PRELIMINARY INVESTIGATIONS

(b) METHOD.

The voltage used on these tests was secured from the step-up transformers described in "APPARATUS". The frequency was 60 cycles at all times and the various voltages were obtained by the series potentiometer control in the transformer primaries. Oscillograms on Plate IV show the wave form of electromotive force. It is evident that this is very close to a sine wave, only a slight distortion occurring because of the introduction of series resistance. This result is probably due to the use of the 46.5 ohms placed in parallel across the transformer primaries. The potentiometer resistance gave a very fine control. The same gradual and uniform rise of voltage from zero to breakdown value was thus possible for all samples. In the preliminary tests, this rise was at the rate of approximately 500 volts per sec. on the high tension side.

The samples were about five inches square for the single layer tests, and increased in size for the multiple layer tests in order to prevent surface discharge. Great care was taken to remove all dust from them as well as from the electrodes. In the multiple layer tests care was taken to place the sheets so that no air bubbles remained between them. In the preliminary tests, 10 mill Empire Insulating Cloth and 24 mill Pressboard were used, samples of which are given on Plate VIII.

The breakdown voltage was obtained by multiplying the reading of the voltmeter across the transformer primaries by the ratio of transformation, which was 1:200. The voltage recorded is the mean effective value. The maximum value is obtained by multiplying the

recorded value by 1.414, since the impressed pressure wave was a sine wave.

III PRELIMINARY INVESTIGATIONS

(c) DISCUSSION OF DATA

The first type of electrode tried was the flat circular disc numbered one to four inclusive on Plate II. This had sharp square corners and varied from one to four inches in diameter. The tests soon showed that corona formed at a very low voltage, approximately 2000 volts, increasing in area with increasing pressure. The intensity which was greatest at the edge of the electrode, gradually decreased outward. The voltage at which corona was first visible did not appear to differ materially with the size of the terminal. The majority of the breakdowns of the insulation occured at the edge of the electrode - the region of greatest apparent stresses.

The data given on Sheets A,B,C,D,E, show the results obtained. Ten mill Empire Insulating Cloth in one and two layers, a sample of which is given on Plate VIII, was tested. Curves plotted from this data, (see Plate V.) are of the same general form. The results,which are highly erratic, show the greatest uniformity with the 2 inch terminal. From the general forms of the curves it also appears that of the four terminals used, the two inch is the best size. The non-uniformity of the results, the intense corona at breakdown and the impossibility of correctly estimating the stresses occurring at the edges of the electrode where the insulation ruptured, indicated clearly that some other form of terminal was necessary.

It seemed possible to improve these conditions by a terminal which would distribute the electrostatic field. Electrodes Nos. 6 and 8 were then designed with this object in view. These are shown on Plate II. Visible corona formed at about the same voltage as with the

electrodes used in the previous experiments. The area and intensity of corona, while not as great as in the first tests, were still sufficient, in most cases, to cause the insulation to break down at the edge of the terminals. Results of these tests are given on Sheet A. A somewhat greater uniformity is apparent with these than with the Nos. 1 to 4 inclusive. A decrease in the number of breakdowns at the edge indicated a decrease of the stresses here, but the presence of an intense electrostatic field at this point showed clearly that an effort to further reduce this phenomenon was highly desirable. Previous tests had shown that Empire Insulating Cloth was not uniform in quality. For this reason, 24 mill Pressboard was now selected as more uniform and homogeneous. Comparison tests were then made with the various forms of electrodes thus far used, and with terminals Nos. 5,7, 9 and 10. The results of these comparison tests are given on Sheets C, D, and E. It is again noticeable from Plate V, on which data obtained for electrodes Nos. 1-4 with 24 mill Pressboard is plotted, that some change occurs at or between the 2 and 3 inch electrodes. The data also shows the greatest uniformity with the 2 inch terminal. Nos. 6 and 8 again show greater uniformity than the Nos. 1-4. Rupture at the edge of Nos. 6 and 8 also occured less frequently than with the flat circular type of terminal.

Tests with electrodes Nos. 7,9 and 10 were not encouraging. No. 7 was not studied at any great length. Results with this form were very erratic and rupture occured at various points of the sphere. Another objection to this type is the fact that it does not appear to duplicate normal operating conditions. A combination of No. 7 with No. 3 was also barren of results of any importance. This is clearly evident from the data given on Sheet E. Electrodes Nos. 9 and 10, for which data is also given on Sheet E, gave negative results and do not

appear to be feasible for dielectric testing of insulating material. Both have the elements of crossed wires, a condition to be found in practice. No. 10 could also be admirably adapted to tests with varying temperatures by sending heated oil or other fluid thru the tubes covered with the dielectric. Its application would, however, be limited to the more flexible forms of insulating material.

Electrode No. 5 which consisted of a 2 inch flat circular disc and a guard ring insulated therefrom, was tried. The results of these tests are given on Sheets F and G, for one and two layers of Empire Insulating Cloth and for 24 mill Pressboard. An inspection of this data shows much greater uniformity than with the other types. Breakdown occured at the edge of the guard ring in some cases though not as frequently as with the other forms of terminals. Corona appeared at perhaps a slightly higher voltage and for breakdown values, was not as intense as in the previous tests. The results obtained with this type were so encouraging that further tests were made. These will be described in the second part of this thesis.

III - PRELIMINARY INVESTIGATIONS

(e) Summary.

At this stage of the investigation it is possible to summarize the results of the tests in the following manner.

(1) The ordinary flat circular disc does not lend itself to the testing of the dielectric strength of insulating material.

(2) Electrodes Nos. 6 and 8, while an improvement upon the flat circular disc, seem also unsuited for testing dielectrics.

(3) Electrodes Nos. 7,9 and 10 gave results which do not recommend them for testing purposes.

(4) Some form of electrode which either distributes the intense electrostatic field occuring at sharp edges or eliminates it entirely, is the form best adapted for dielectric testing purposes.

(5) A two inch terminal appears to be the best size, giving sufficient contact surface and the greatest uniformity of results.

(6) An electrode like No. 5 gave the best and most uniform results.

(7) From a few observations, it appears that the time rate of voltage rise is an important element in determining the breakdown pressure.

(8) To obtain comparative results, it is necessary that all conditions should be exactly similar in all of the tests.

METHODS OF TESTING SOLID DIELECTRICS

III- PRELIMINARY INVESTIGATIONS.

(d) Data.

Comparison Test of Electrodes.

Rupture Voltages.

Single Layer .01 in. Empire Insulating Cloth.

Test No.	Electrode No.						
	1	2	3	4	5	6	8
1	5000	6800	6900	3400	8300	7000	9000
2	6600	7100	5600	3200	8800	6000	9670
3	6600	6500	6600	4400	8800	6400	9450
4	8000	7200	5000	4600	8900	6200	8550
5	7100	5700	6400	4900	8800	6200	8700
6	4000	5700	6600	4600	8700	6400	8850
7	6800	5000	5600	3300	9000	6200	8250
8	7300	6800	6500	6200	8600	7200	7350
9	7600	6400	5500	5800	9000	6800	9600
10	7900	6100	4200	5600	-----	7000	8850
Av.	5690	6330	5890	4600	8745	6540	8830

Temperature - 20°Centigrade.

Weight used, 3 lb. 6 oz.

Average rate of rise of voltage, 500 volts per second.

METHODS OF TESTING SOLID DIELECTRICS

III- PRELIMINARY INVESTIGATIONS

(d) Data.

Comparison Test of Electrodes.

Rupture Voltages.

Two Layers .01 in Empire Insulating Cloth.

Test No.	Electrode No.						
	1	2	3	4	5	6	8
1	9600	10000	11000	10600	15300	10000	17150
2	8800	9400	10800	8800	15600	10600	17850
3	8700	9200	11600	9700	15200	10300	17200
4	8000	9400	11100	9600	15200	10200	18000
5	8000	9300	11300	10800	14800	9900	17900
6	7600	7800	11300	10000	17200	10200	15300
7	7000	11600	11100	10600	16600	10100	16800
8	8000	11300	11100	10600	----	10600	16100
9	8000	----	10600	9400	----	10100	16900
10	8000	----	11000	8600	----	12400	17200
Av.	8170	9775	11090	9860	15900	10440	16940

Temperature - 20°Centigrade.

Weight used, 3 lb. 6 oz.

Average rate of rise of voltage, 500 volts per second.

METHODS OF TESTING SOLID DIELECTRICS

III- PRELIMINARY INVESTIGATIONS.

(d) Data.

Comparison Test of Electrodes.

Rupture Voltages.

One Layer .024 in. Pressboard.

Test No.	Electrode No.						
	1	2	3	4	5	6	8
1	11300	10000	7200	7000	7400	----	----
2	10800	9400	7000	8200	7600	----	----
3	9000	9800	9600	7400	7000	----	----
4	10000	10000	9000	5000	7400	----	----
5	10200	9200	8200	6400	7400	----	----
6	10400	9200	9600	7600	7200	----	----
7	10700	9300	8200	7200	7300	----	----
8	10100	9000	9400	7300	7300	----	----
9	9900	9000	9900	6400	7700	----	----
10	9700	8600	9300	6400	7500	----	----
Av.	10210	9350	8740	6890	7380	----	----

Temperature - 20°Centigrade.

Weight used, 3 lb. 6 oz.

Average rate of rise of voltage, 500 volts per second.

METHODS OF TESTING SOLID DIELECTRICS

III- PRELIMINARY INVESTIGATIONS.

(d) Data.

Comparison Test of Electrodes.

Rupture Voltages.

One Layer .024 in. Pressboard.

Test No.	Electrode No.				
	#7 over #3	6	8	9	10
1	6800	8800	7200	10400	10600
2	10400	9600	7350	10000	14100
3	10400	8200	7350	12800	10500
4	9600	8800	7260	13400	13700
5	9600	7200	6500	12600	13800
6	11200	6800	7260	11200	9300
7	-----	7200	7950	13600	12200
8	-----	8000	7660	14400	12400
9	-----	8000	6750	12700	14500
10	-----	8400	7350	-----	15800
Av.	8000	8100	7263	12345	12690

Temperature - 20°Centigrade.

Weight used, 3 lb. 6 oz.

Average rate of rise of voltage, 500 volts per second.

METHODS OF TESTING SOLID DIELECTRICS

III-PRELIMINARY INVESTIGATIONS.

(d) Data.

Comparison Test of Electrodes.

Rupture Voltages.

Two Layers .024 in. Pressboard.

Test No.	Electrode No.				
	1	2	3	4	5
1	20100	16700	15400	12400	17900
2	20300	16800	15400	10000	15700
3	19300	17200	15100	10800	16800
4	19400	17500	15200	10800	17600
5	18900	16700	16600	15600	16900
6	19500	19800	15600	15000	17500
Av.	19580	17450	15550	12433	17065
	#7 over #3	6	8	9	10
1	14000	13200	15450	22800	18800
2	16000	16400	14850	23400	19500
3	15000	15000	14550	21600	21000
4	19000	14800	15450	20600	19400
5	13000	15800	15750	-----	22600
6	-----	12800	16000	-----	22700
Av.	15400	14667	15340	21950	20486

Temperature - 20°Centigrade.

Weight used, 3 lb. 6 oz.

Average rate of rise of voltage, 500 volts per second.

IV- FURTHER THEORY.

The preliminary investigations showed clearly that in order to obtain comparative results, extreme care was required to exactly duplicate conditions in all the tests. A consideration of the factors influencing the results is of interest at this point.

It was discovered that tests upon two or more layers of material were extremely difficult at first. The trouble was traced to the fact that any air bubble or wrinkle tending to form an air pocket was a point of breakdown. The reason for this is readily understood from the reasoning given in "GENERAL THEORY", viz.,the potential gradient in this air pocket or film becomes great enough, due to the low specific inductive capacity of the air, to break down the latter. As a result, intense heating occurs at this point and progressive breakdown of the insulation is probably the result. This would seem to indicate that when building up an insulating wall in practice, too great care cannot be given to the way in which the layers of the dielectric are put together.

In the summary of the preliminary investigations, #7 deals with the rate of rise of voltage. It was found that by increasing the rate, an almost unlimited variation in breakdown pressure was obtainable. If the theory of stresses within the dielectric, as developed in "General Theory" is correct, it would follow that this is the result which might be expected. Thus, the stresses in any material under test, occur only after the application of a definate amount of energy; for example, tensile tests of steel etc. If this is true for dielectrics it would seem reasonable to suppose that not only high pressure but a certain minimum amount of energy for a definate time is required to rupture the insulating material. The results of some

observations seem to substantiate this. The tests made showed that after a certain minimum rate of rise in voltage was reached, a further reduction of this rate did not result in a different value of rupture voltage. In the final tests, results of which are given in the following pages, this rate for the material and electrodes used, was about 200 volts per second.

In the early tests it was discovered that particles of dust were points about which intense corona formed. Based on the electronic theory, this may be due to the radioactive property of the dust particles which cause them to ionize the air in their vicinity, or it may be equivalent to a roughness or sharpness of the electrode and hence the cause of a high intensity electrostatic field at this point. Whatever may be the true explanation, investigators of corona losses on transmission lines are agreed that the presence of dirt on the conductors is a source of corona formation. In these tests it was seen that the great stresses present where corona is formed, were highly detrimental to success in dielectric testing. For this reason it is highly advisable that in building up insulating walls the question of dust or dirt between the component parts is one which should receive due consideration.

Thus far in the discussion and investigation, the question of the electrostatic field was of paramount importance. Some method of reducing this intense fringing field seemed advisable. Electrode No.5 shown on Plate II, appeared to promise relief in this matter. As was expected, it was discovered that the field within the guard ring was parallel and uniform in intensity at all points. This was due to the confining action of the field outside of the electrode. However, at the ring's edge the same intense field requires consideration. If now this field is so dissipated that the potential gradient at all points

thru the dielectric is small, no harm results. This was made possible by lengthening the air path in the exterior field, thus increasing the drop of voltage thru the air and reducing the gradient thru the dielectric.

If the ring is insulated from the inner electrode, the charge on it is that due to induction. This charge will not be as intense as if the ring were directly connected to the main terminal, due probably to the neutralizing action of the charge induced by the lower terminal. The net result is that the inner field is a uniform one while the surrounding field is a comparatively weak one, and hence rupture of the insulation occurs within the strong uniform field.

The tests made for this thesis showed again that the dielectric strength of insulating material does not vary directly with the number of layers. It seems possible from the preceeding analysis of conditions to see the probable cause for this result. The complex insulating wall will not be homogeneous but will consist of air films and layers of material having a skin hardness due to finishing. This non-uniform grading of material will cause different potential gradients to exist in each of the component parts of the built-up wall. If the dielectric strength of any of these component parts is exceeded, breakdown will occur at this point and the resultant heating and increased strain in the remaining parts ultimately results in complete rupture. This phenomenon is more clearly evident in such dielectrics as varnished fabrics, Empire Insulating Cloth for example. With that material, a number of layers will have the insulating compound unequally distributed as is indicated by Sketch E. Thus two layers of insulating material are close together, changing the slope of the gradient at that point and resulting in a large gradient in the parts next to the

Sketch E.

electrodes.

A consideration of the facts brought out in the preceeding paragraph, show that by a proper grading of the thickness and the spacing of the various parts of the complex dielectric, it should be possible to increase the strength of a built-up insulating wall. In the Empire Insulating Cloth, a cotton fabric serves as a basis. This is coated with a layer of insulating material on both sides. Plate VIII shows clearly that this substance does not completely penetrate the cotton foundation. This then, gives a dielectric which cannot be considered as homogeneous and hence, two layers of Empire Insulating Cloth are equivalent to a compound dielectric made up of several parts This compound insulating wall will not have its parts uniformly distributed, consequently the stresses on the various parts will not be the same. It seems that the introduction of cloth between the two layers would give greater uniformity of distribution of material.

It is evident that the subject of insulation presents a field for much work. In the tests, a description of which follows, some of the points brought up in the exposition have been investigated and the results are discussed.

V- FINAL INVESTIGATIONS.

(a) APPARATUS AND METHODS.

The apparatus was that used in the previous tests with the exception of the transformers. During a portion of these latter tests two 110-33000 Volt, 200 Watt, General Electric Co's. Instrument Transformers were used. These each took a charging current of about half an ampere on 110 volts. Plate III shows the charging current taken at the various voltages. The electrode had the form and dimensions indicated on Plate II. Terminal No. 5 was used over No. 3. The guard ring was raised .048 in. above the lower terminal and insulated from the upper disc by a layer of Empire Insulating Cloth. All parts of the terminal were well finished and the face highly polished. The electrode was kept clean at all times and the insulating collar frequently renewed to remove accumulated dust and carbon.

The voltage control was the same as in the former tests but the rate of voltage rise in this case was 200 volts per second. All transient effects were avoided by careful manipulation of the control device. By calibrating the voltmeter it was possible to obtain the same rate of voltage rise for all samples. A stop watch was used to obtain time from the beginning of the test to the instant of rupture, a check being thus secured upon the uniformity of the rate.

The samples varied in size, depending upon the probable rupture voltage. With the higher pressures it was found necessary in order to save material and to prevent surface discharge, to construct a shield of Empire Insulating Cloth to which the material, both cloth and pressboard, was made to adhere. With the very high voltages, a guard ring of #8 B.&S. brass wire, 4 in. in diameter, laid on the material under test and concentric with the terminals, effectively

prevented surface spark discharges. In building up the layers, great care was used to remove all dirt from the samples and to place the sheets together so that air pockets and wrinkles were eliminated as far as possible.

All these tests were made under conditions such that the moisture content of the air was about the same at all times. The temperature varied very little during any continued test and averaged 20° Centigrade. The weight used on the upper standard to secure good contact of the insulating material and the electrodes, was varied with the number of layers in order to give at all times about the same uniformity of contact. For the one and two layer tests this weight was about 17.2 oz. per square inch while for the three and four layer ones it was 33.7 oz.

V- FINAL INVESTIGATIONS.

(b) DISCUSSION OF DATA.

1-Pressboard.

This material was of a uniform thickness of .024 inches, and a sample of it is shown on Plate VIII. Tests of one, two, three and four layers of this were made. The data obtained is given on Sheets F,G,H, and I, and curves of the data are shown on Plate VII. A net weight of 3 lbs. 6 oz. was used with the one and two layers to secure firm contact with the electrodes. With the three and four layers, the weight was increased to 6 lbs. 10 oz.

The results were very uniform and breakdown regularly occured within the inner electrode. Heating under the guard ring, for the lower voltages, was inappreciable and even with the higher voltages was not sufficient to cause rupture under the ring. The curve plotted from this data is nearly a straight line showing an almost direct variation of dielectric strength with the thickness of a homogeneous material.

As previously suggested, the hardness of the outside of the pressboard due to skin effect in finishing the material will affect the strength of a built-up insulating wall. In many of the tests made upon this material, charring occured between the layers at the point of rupture which seems to indicate progressive breakdown. The charring was not deep and would, according to the reasoning in "GENERAL THEORY" be due to the formation of corona between the layers. This corona might be especially large if the contact between the layers be poor, and if the inductivity of the surface skin be high. This charring action emphasizes the importance of the suggestion in "FURTHER THEORY" regarding the building up of insulating walls in practice, viz., extreme care should be taken to secure perfect contact between layers.

The uniformity of the results obtained in these tests suggests that this material is a very reliable one. The dielectric strength is approximately 300 volts per mill and it appears reasonable to assume that up to a thickness of about 72 mills, the dielectric strength of a single sheet could be taken as 300 times the thickness in mills.

V- FINAL INVESTIGATIONS.

(b) DISCUSSION OF DATA.

2-Empire Cloth.

Samples of this material are shown on Plate VIII. Various weights and qualities of this cloth are made but the tests were confined to three thicknesses of one quality, viz., 10, 12 and 15 mill, and one other quality of a thickness of 7 mills. It is evident that this material is not as uniform in quality as the pressboard. This is clearly shown by the results. Tests were made upon one and more layers of the various thicknesses and this data is given on Sheets F,G,H, and I. Curves plotted from this data are shown on Plate VII. The same weights were used in these tests as with the pressboard, and the voltage rise was 200 volts per second.

The non-uniformity of the results of these tests was probably due to, (1) the composite nature of the material, (2) the unequal distribution of the insulating compound (the surface of the cloth was frequently full of tiny bubbles thru one or more of which rupture often occured). The data shows that the dielectric strength of the cloth does not vary directly with the thickness. It seems, however, that after a thickness of material is reached at which the cloth foundation is a small percentage of the total thickness, the strength is more nearly proportional to the thickness.

A few tests conducted with a number of layers each separated from its neighbor by a thin sheet of cheese cloth, gave the compound dielectric a much higher strength than the simple built-up wall used in the tests made for this thesis. Thus, two layers of the 10 mill Empire Cloth with a layer of 6 mill cheese cloth between, had a dielectric strength of about 16000 volts. This increase in strength cannot be credited to the dielectric strength of the cheese cloth or to the air space produced by it. It must therefor be due to the changing of the potential gradient within the complex dielectric so as to give more favorable conditions at all points.

The curves for the multiple layer tests of this material have the same form - given by $KV = t(K_1N - K_2N^x) - \frac{K_3N}{t}$ specifically, $KV = t(.9N - .06N^2) - \frac{4.5N}{t}$ where "t" is the thickness in mills; "N" is the number of layers, K_1, K_2, and K_3 are constants, and "x" is about 2. (see footnote)

In the tests made with this material using multiple layers charring action and chemical disintegration occured at the rupture point in many instances. This was probably due to local heating caused by corona in an air pocket between the layers at that point. The statement made in regard to the care required in building up dielectric coatings is especially to be noted in connection with insulating cloths of this character. The unequal distribution of the insulating coating makes this material less reliable than the pressboard. For general use it seems that single layers of Empire Cloth vary in dielectric strength almost in proportion to their thickness. Approximately the strength per mill is 750 volts.

---:::---

NOTE:- Equations which check fairly well with observed values are;

	PLATE VI	PLATE VII
Curve #6	$V = 1520\,T - 7600 - \left(\frac{T}{6.5}\right)^{9.8}$	#1 $V = 6800N - 216N^{2.2}$
" 7	$V = 3000\,T - 1400 - .0065\,T^{5.2}$	2 $V = 7600N - 12\,N^4$
" 8	$V = 4120\,T - 20000 - 1.32\left(\frac{T}{4.23}\right)^{7.2}$	4 $V = 10200N - 257N^{2.5}$
		5 $V = 12300N - 200N^3$

METHODS OF TESTING SOLID DIELECTRICS

V- FINAL INVESTIGATIONS.

(c) Data.

Tests made with Guard Ring Type of Electrode.

Rupture Voltages.

Tests on Single Layer.

No.	.007" Volts	EIC Sec.	.010" Volts	EIC Sec.	.012" Volts	EIC Sec.	.015" Volts	EIC Sec.	.024" Volts	P.Bd. Sec.
1	6750	38	7500	41	10200	51	13100	64	7200	36
2	7200	36	7800	45	10500	52	12500	60	7500	40
3	6400	32	7400	42	10100	50	12900	64	7600	36
4	6600	34	7800	42	10350	52	11550	57	7000	35
5	7260	39	7100	38	10500	54	13100	61	7300	35
6	7380	43	7400	43	10400	52	12550	62	7400	43
7	6750	35	7900	46	10050	51	11700	57	7300	36
8	7120	38	7700	43	10350	51	12200	60	7300	36
9	6300	31	7900	47	10150	51	11800	60	7400	32
10	7400	38	7200	41	10050	51	11700	58	7400	38
Av.	6916	36	7570	42.8	10265	51.5	12315	60.3	7340	36.7

"EIC" is Empire Insulating Cloth. "P.Bd." is Pressboard.

Weight used, 3 lb. 6 oz. or 17.2 oz. per sq. in.

Temperature - 20°Centigrade.

Average rate of rise of voltage, 200 volts per second.

METHODS OF TESTING SOLID DIELECTRICS.

V- FINAL INVESTIGATIONS.

(c) Data.

Tests made with Guard Ring Type of Electrode.

Rupture Voltages.

Tests on Two Layers.

No.	.007" Volts	EIC Sec.	.010" Volts	EIC Sec.	.012" Volts	EIC Sec.	.015" Volts	EIC Sec.	.024" Volts	P.Bd. Sec.
1	12150	56	15000	73	19000	94	23600	100	14700	73
2	12300	61	15000	74	19200	99	23400	99	15000	73
3	12750	61	15300	77	18000	90	22500	90	14850	72
4	12300	60	15000	73	19300	99	23500	94	14850	72
5	12800	63	15200	74	19300	97	23400	93	15300	76
6	12300	60	14850	72	19000	92	22800	98	15450	76
7	13500	68	15700	74	18450	92	22500	94	15000	72
8	12350	60	14750	70	19000	92	22200	94	15250	74
9	12300	60	15300	75	19500	87	23500	97	15100	74
10	12150	58	14850	72	18900	96	22600	98	14850	73
Av.	12585	61	15035	73.4	18965	94	23000	96	15035	73.5

"EIC" is Empire Insulating Cloth. "P.Bd." is Pressboard.

Weight used, 3 lb. 6oz. or 17.2 oz. per sq. in.

Temperature - 20°Centigrade.

Average rate of rise of voltage, 200 volts per second.

METHODS OF TESTING SOLID DIELECTRICS.

V- FINAL INVESTIGATIONS.

(c) Data.

Tests made with Guard Ring Type of Electrode.

Rupture Voltages.

Tests on Three Layers.

No.	.007" Volts	EIC Sec.	.010" Volts	EIC Sec.	.012" Volts.	EIC Sec.	.015" Volts	EIC Sec.	.024" Volts	P.Bd. Sec.
1	17900	88	20400	89	26700	131	29700	140	24150	114
2	19000	96	19500	85	26700	140	31400	142	24100	113
3	17750	89	20300	85	27600	138	31000	147	23400	109
4	17250	85	20750	88	25900	127	29800	140	25300	126
5	18000	89	20600	91	27200	139	31700	145	23100	108
6	18900	93	21700	99	27600	140	31100	143	25650	127
7	17400	82	21100	92	25500	124	31200	143	22500	105
8	18300	88	21500	98	26700	128	32600	147	23100	112
9	19000	95	20700	96	26800	137	31800	139	20400	93
10	17100	84	19700	85	25300	122	32100	142	22600	111
Av.	18060	89.6	20625	92.8	26600	133	31240	143	23430	110

"EIC" is Empire Insulating Cloth. "P.Bd." is Pressboard.

Weight used, 6 lbs. 10 oz. or 33.7 oz. per sq. in.

Temperature - 20°Centigrade.

Average rate of rise of voltage, 200 volts per second.

METHODS OF TESTING SOLID DIELECTRICS.

V- FINAL INVESTIGATIONS.

(c) Data

Teats made with Guard Ring Type of Electrode.

Rupture Voltages.

Tests made on Four Layers.

No.	.010" Volts	EIC Sec.	.012" Volts	EIC Sec.	.024" Volts	P.Bd. Sec.
1	27300	124	31500	155	29300	141
2	26200	137	30750	144	27600	118
3	27000	135	33600	161	30500	146
4	28100	124	33500	158	28900	134
5	26200	137	33000	133	27800	132
6	27000	135	-----	---	28100	121
7	25300	122	-----	---	30200	143
8	27600	142	-----	---	-----	---
9	26200	128	-----	---	-----	---
Av.	26765	131.5	32450	150	28910	133.5

"EIC" is Empire Insulating Cloth. "P.Bd." is Pressboard.

Weight used, 6 lbs. 10 oz. or 33.7 oz. per sq. in.

Temperature - 20°Centigrade.

Average rate of rise of voltage, 200 volts per second.

VI- CONCLUSIONS.

The results of these tests may be summarized as follows:

1- An electrode of type No. 5 gives very uniform and reliable results.

2- The time rate of increase of impressed voltage is an important factor in determining the rupture value. It appears that a rate may be determined which will give results that are consistent at all times for the given material.

3- Test conditions are important. Dust, dirt and other sources of corona formation affect the reliability and uniformity of results.

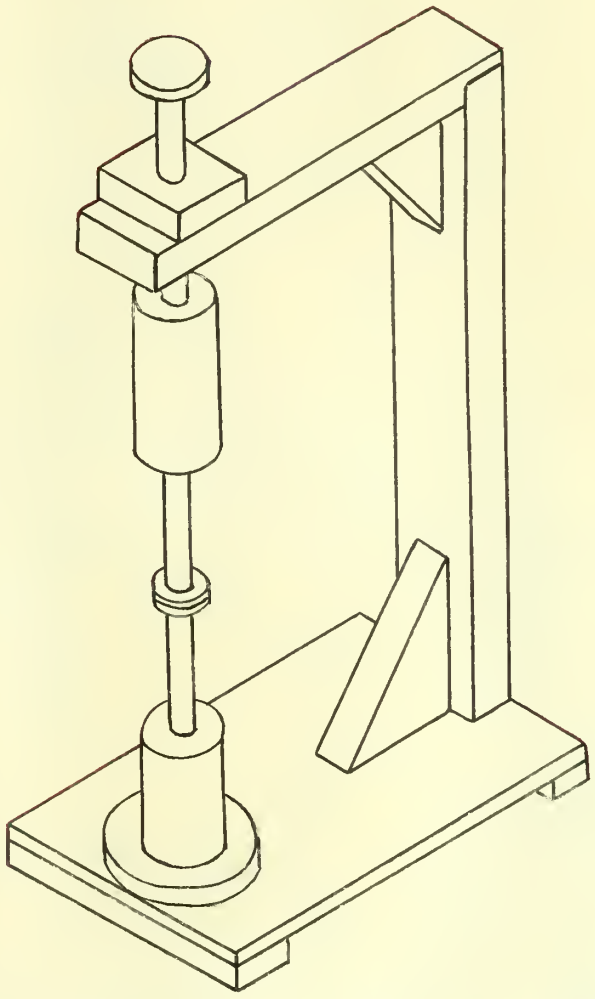
4- The rupture strength of a single layer of homogeneous material, within limits varying with the dielectric, is very nearly proportional to the thickness. With more than one layer, the strength is determined by the degree to which the built-up wall approaches a single thickness in character.

5- Complex dielectrics, as insulating cloths for example, will also have a strength nearly proportional to the thickness of insulating compound if the cloth base is not too great a percentage of the total thickness.

6- Homogeneous dielectrics show greater reliability than the complex ones.

7- In building up insulating walls, it is necessary, in order to secure the most efficient use of the material, that the adjoining surfaces of the layers be absolutely clean and free from air pockets. 8- By properly grading and distributing the various materials in a compound wall, a much greater dielectric strength may be given it than if the specific inductive capacities of the materials were ignored.

PLATE I.



GENERAL VIEW OF APPARATUS

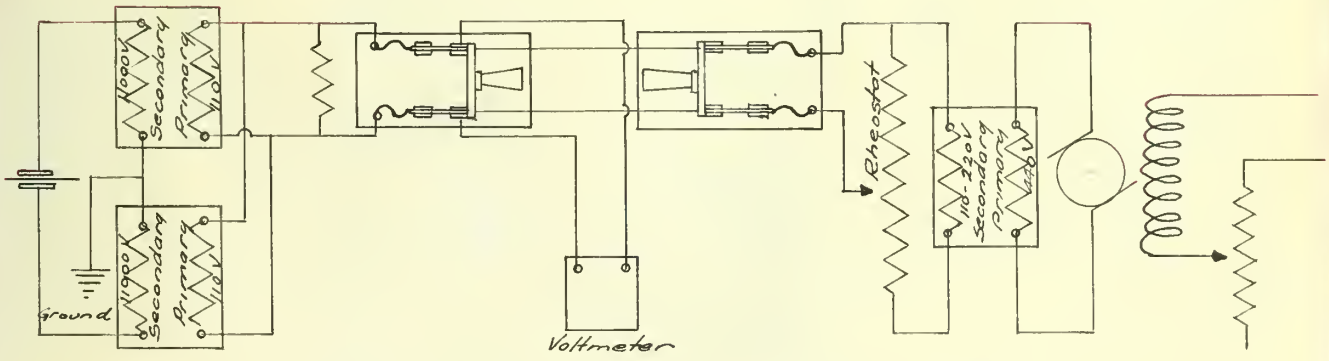
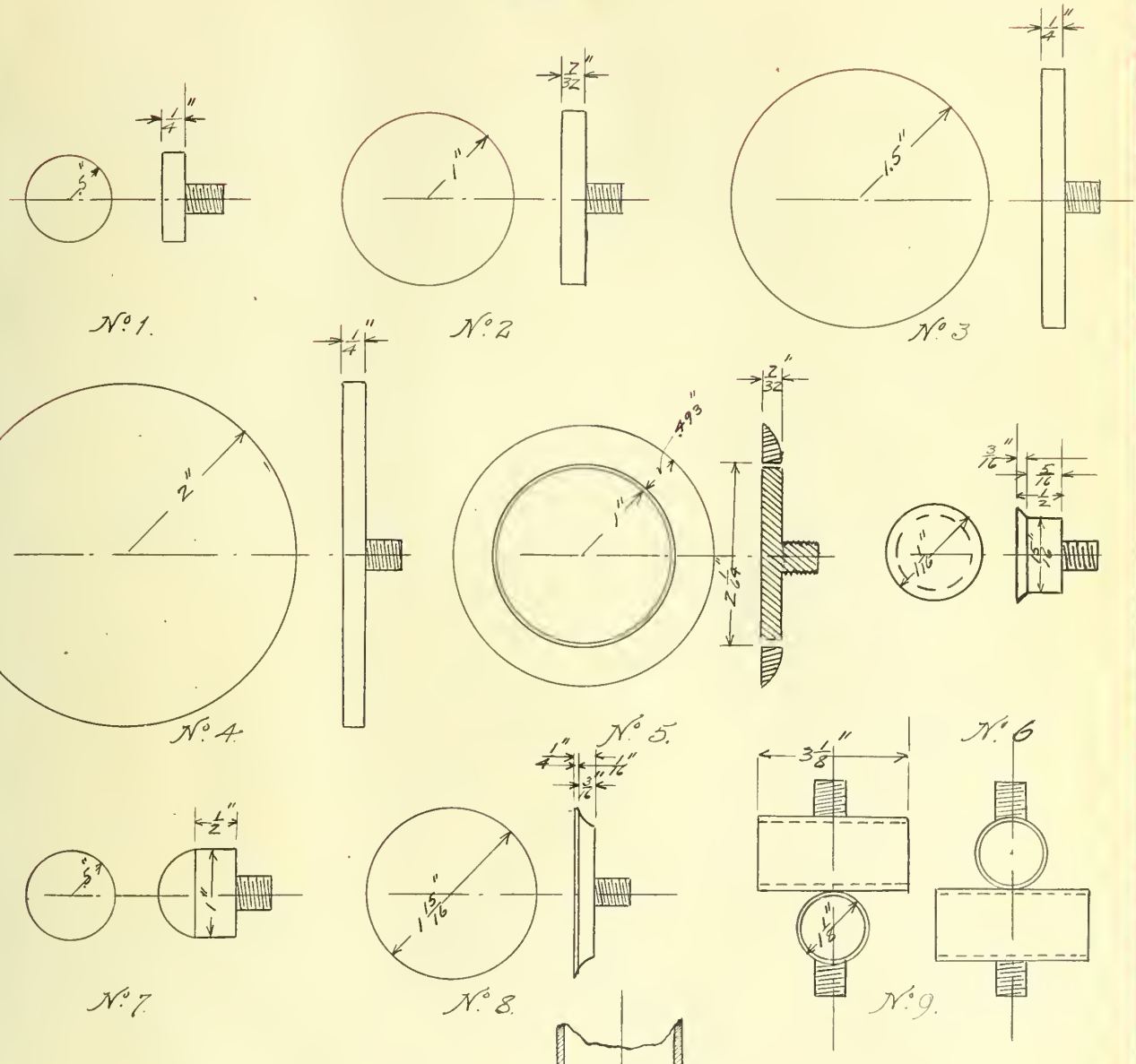
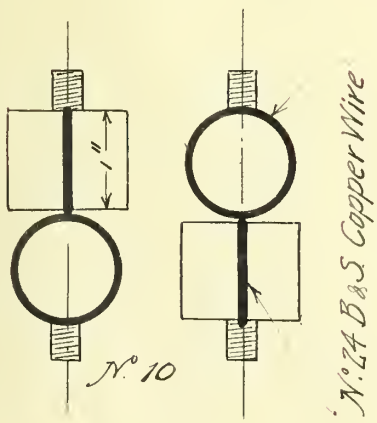
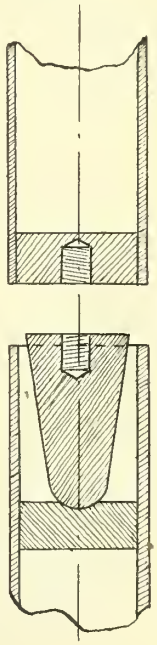


DIAGRAM OF CONNECTIONS

PLATE II.



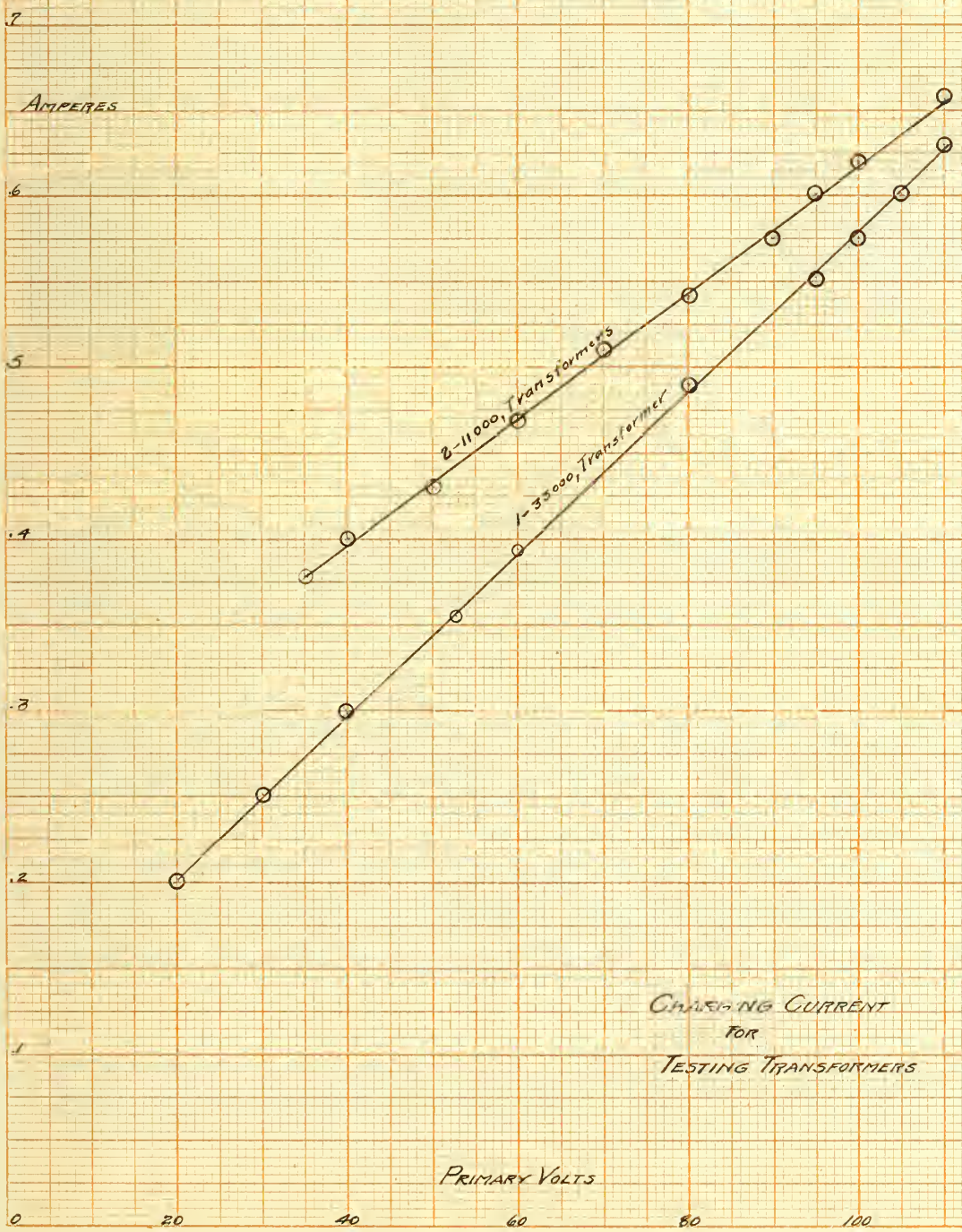




— Self Adjusting Terminal Seats. —

TERMINALS USED ON "INSULATION TESTS OF MATERIALS" BY CAPEK & FOLTZ 1910-1911 THESIS – UNIV. OF ILL.

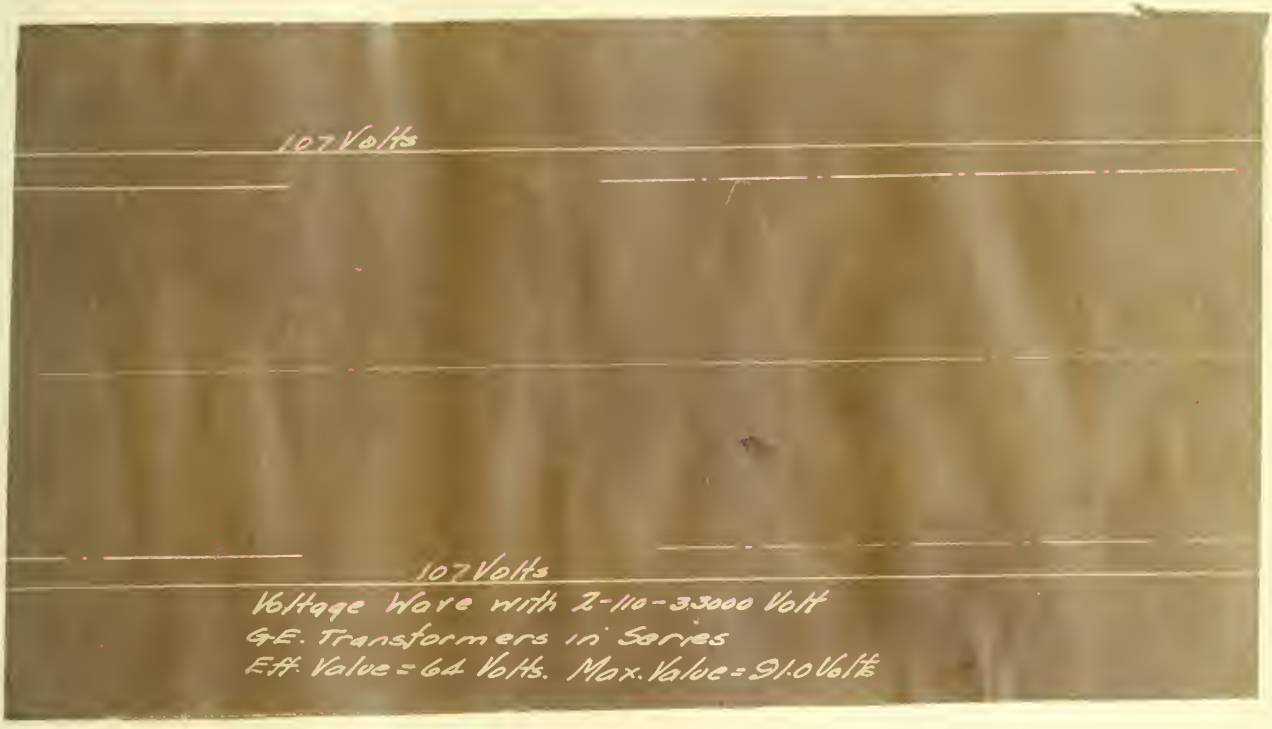
PLATE - III.



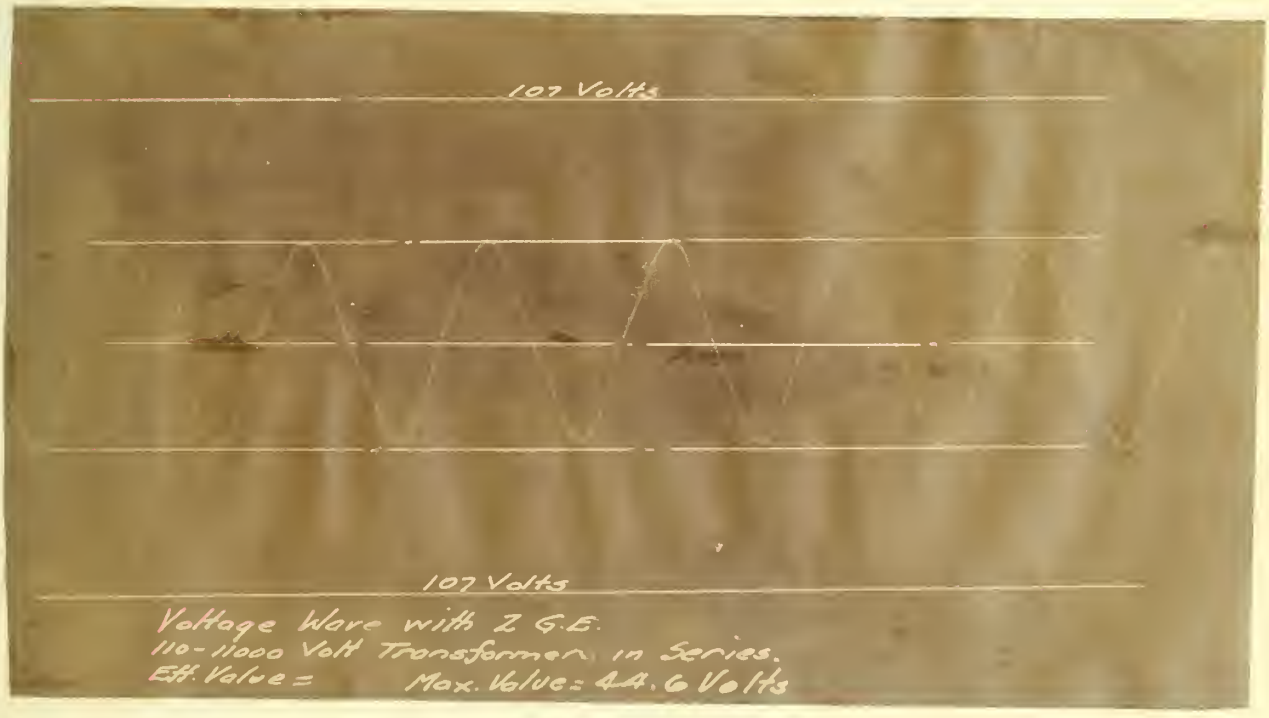
Charging Current
for
Testing Transformers

U. OF I. S. E. FORM 3

----OSCILLOGRAMS, PLATE IV.----

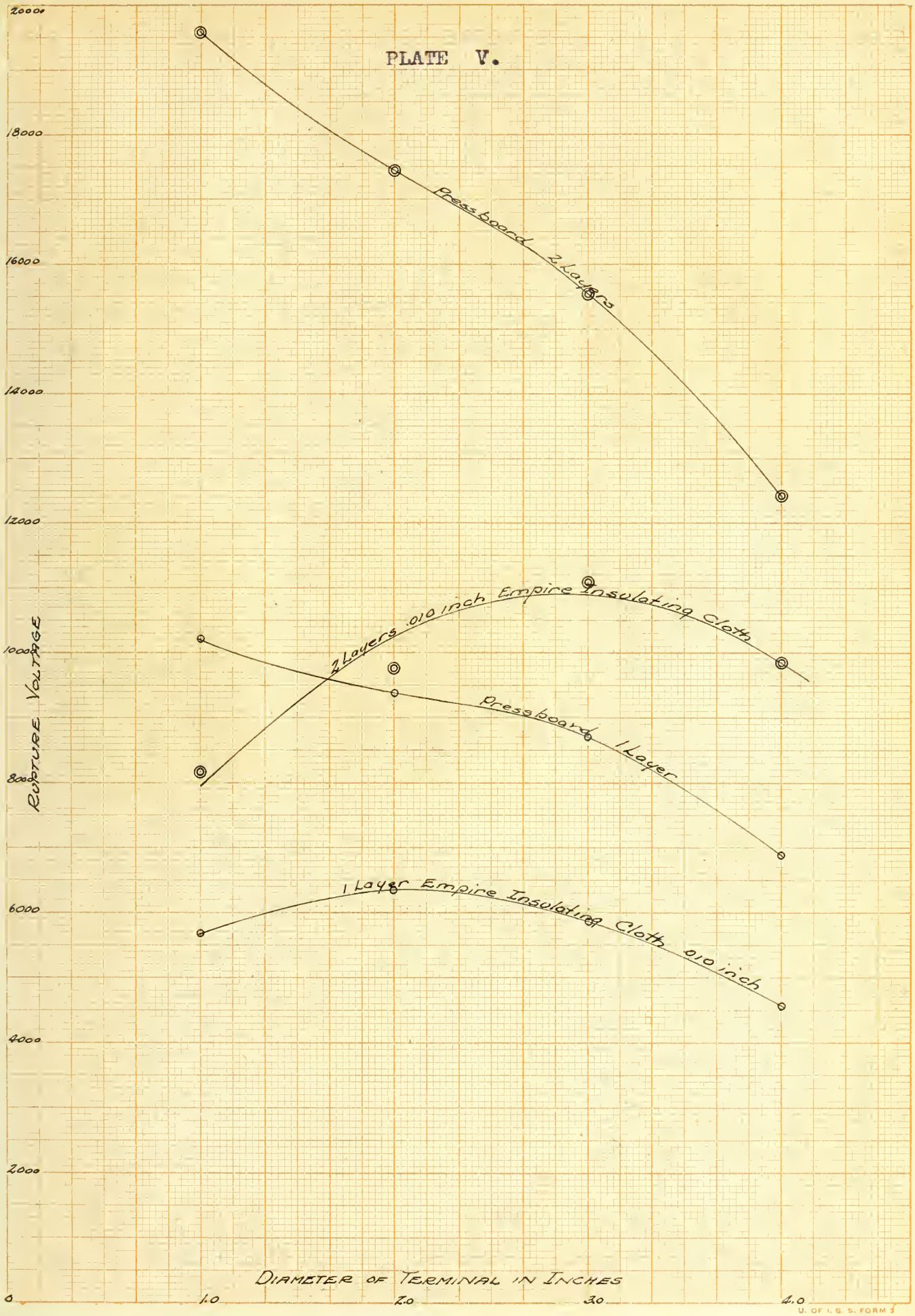


Voltage Wave with 2-110-33000 Volt G.E. Transformers in Series
Eff. Value = 64 Volts. Max. Value = 91.0 Volts



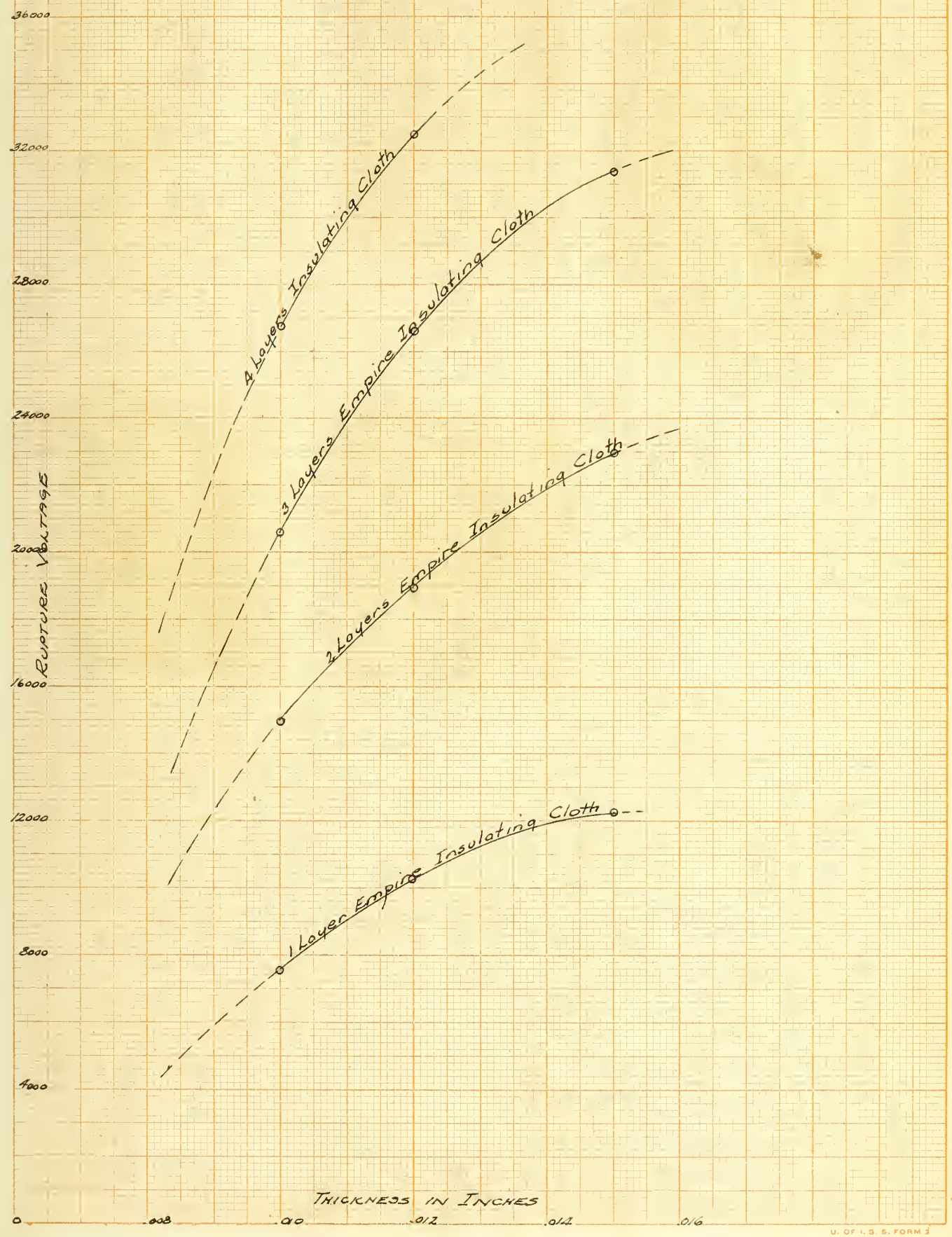
Voltage Wave with 2 G.E. 110-11000 Volt Transformers in Series.
Eff. Value = Max. Value = 44.6 Volts

PLATE V.



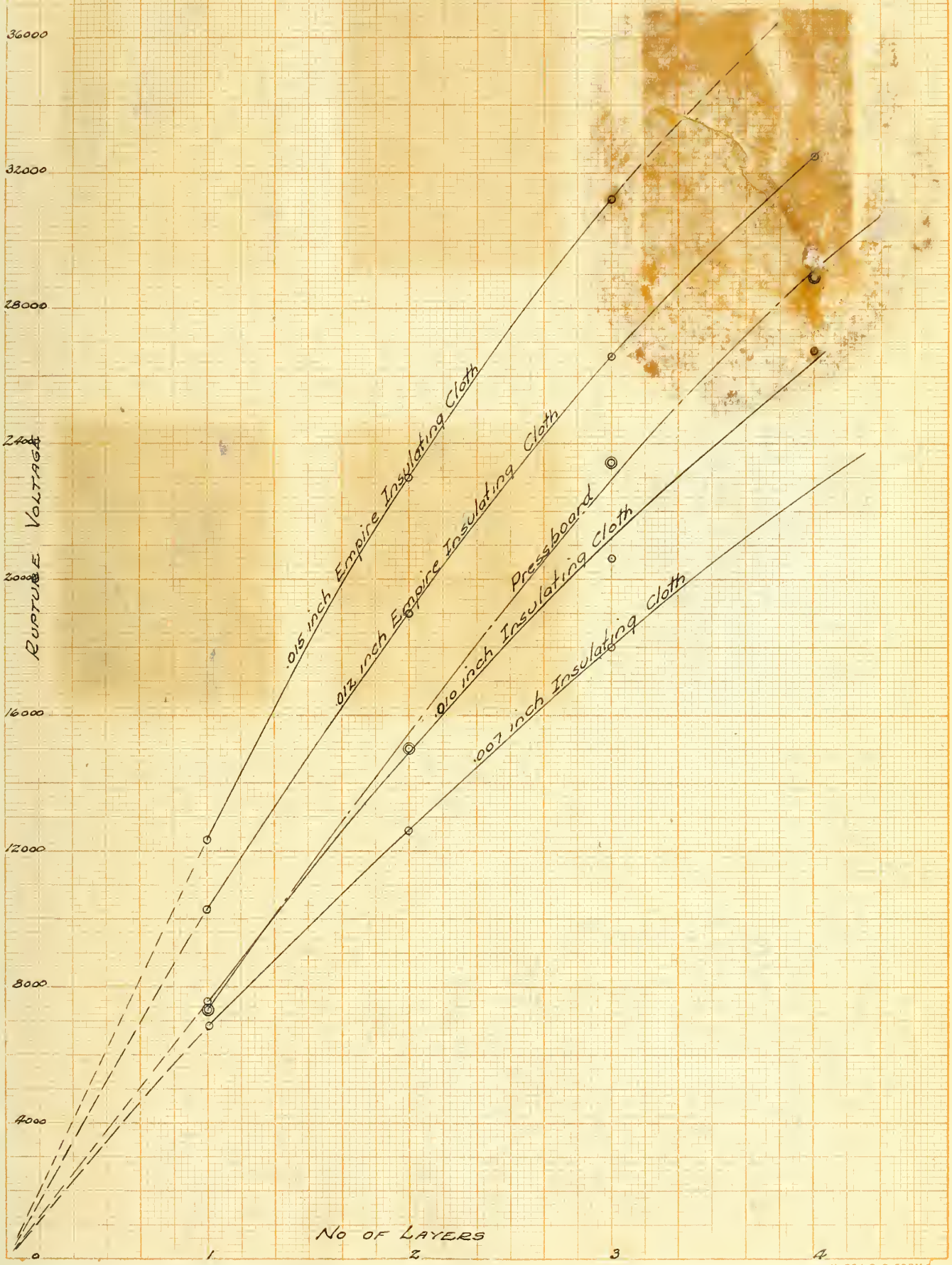
U. OF I. S. S. FORM 3

PLATE VI.



U. OF I. S. FORM 3

PLATE VII.



U. OF I. S. S. FORM 3

PLATE VIII.
EMPIRE INSULATING CLOTH.

.007 in.

.01 in.

.0[illegible] in.

EMPIRE INSULATING CLOTH.

PRESSBOARD.

.015 in.

.015 in.

.024 in.

SAMPLES OF MATERIALS
TESTED.

UNIVERSITY OF ILLINOIS-URBANA
3 0112 079826175